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HORN DESIGN EQUATIONS FOR THE NBS HORN-TYPE NOISE STANDARDS

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CONTENTS

	Page
1. Introduction—Internal Reflections	1
2. Braun Equations	4
3. Sundry Equations	6
4. Results	9
5. Acknowledgments	9
6. References	12
Appendix A: Aperture Reflection	13

Horn Design Equations for the NBS Horn-Type Noise Standards

W. C. Daywitt

Equations are given for calculating the interior dimensions of the horn pickup in the NBS millimeter wave noise standards. These dimensions insure negligible internal horn reflections, resulting in an accurate calculation of the horn attenuation. Measurements in the WR10 horn show a reflection of magnitude less than 0.001.

Key words: electromagnetic horn; millimeter wave; noise source; reflection coefficient.

1. Introduction—Internal Reflections

The National Bureau of Standards (NBS) horn-type cryogenic reference noise standards [1] consist of a noisy cavity and a pyramidal horn pickup. Their output noise temperatures are the sum of the cavity temperature and the excess noise temperature generated by the dissipative horn loss. An accurate calculation of the horn loss requires a knowledge of the magnetic field parallel to the internal horn surfaces, so the horn must be structured to allow for an accurate prediction of that field.

Figure 1 shows an E-plane cross sectional view of one of the millimeter wave horns. The waveguide (wg) and early flare portions are surrounded by a water jacket to maintain them at a uniform temperature close to ambient. As is well known, no solutions for the field patterns inside the pyramidal flare exist. However, by using a gradual (small angle) flare it is possible to maintain the TE_{10} mode field pattern generated in the waveguide portion of the horn far into the flare as long as the discontinuities at the wg-flare transition and at the aperture are minimized.

The wg section of the horn in figure 1 is chosen just long enough to filter out higher-order modes generated in the horn flare by the cavity radiation, but otherwise as short as possible to achieve a minimum loss [1]. In particular, the wg is chosen to keep the output noise temperature due to higher modes below 0.1% of the total output at the highest operating frequency of the noise source. Table 1 is a list of these minimum wg lengths for the wg bands from WR90 to WR10. The first column lists the various wg bands by their WR designations with their corresponding frequency ranges listed in column two. The wg length x_1 required to produce a 0.1% higher mode error is listed in column three. Thus, as long as the wg portion of the horn is x_1 or longer, the output noise temperature of the source is contaminated by less than 0.1% of the higher-mode energy.

A schematic cross sectional view of a horn antenna is shown in figure 2, indicating the wg flange F, the wg-flare butt joint A, and the aperture edges B. The double arrows depict surface currents caused by fields entering the flange and exiting the aperture. Significant diffraction (single arrows) occurs at the joint and aperture because of the abrupt edges at A and B, which in turn disturb the desired TE_{10} mode field pattern and lead to errors in the calculated horn loss.

To reduce the diffraction effect at the butt joint a smooth circular arc from wg to flare is made. Figure 3 shows this transition region for the E- and H-plane cross sections of the horn, where for convenience only the

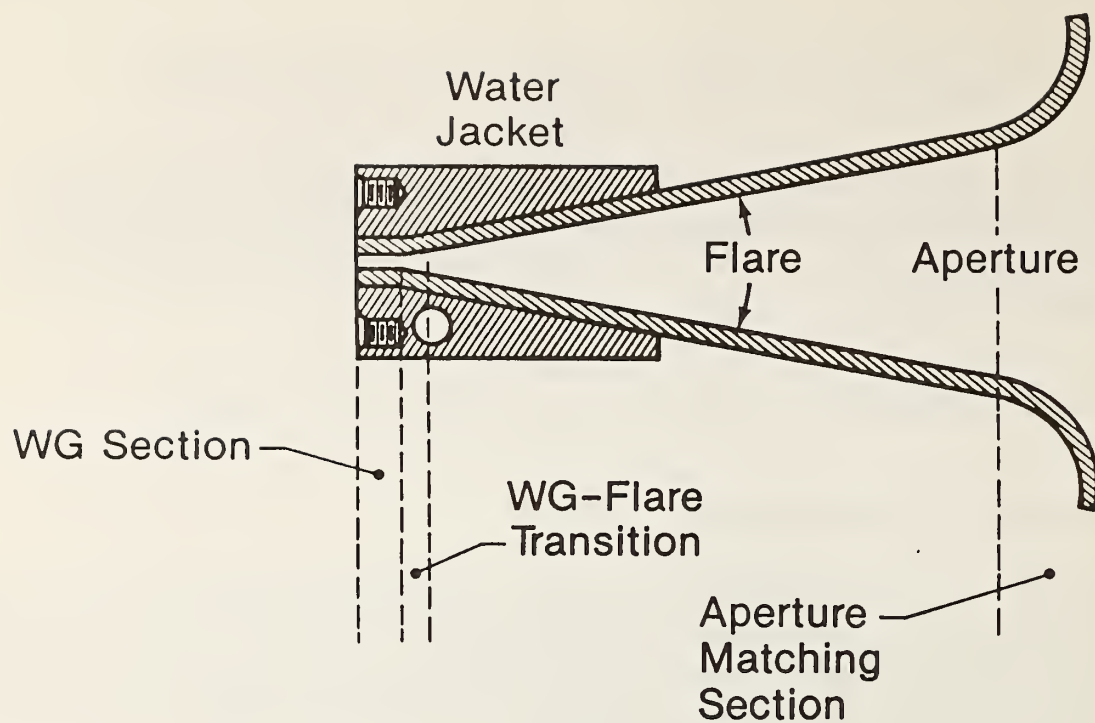


Figure 1. A simplified E-plane cross section of the WR10 millimeter wave horn.

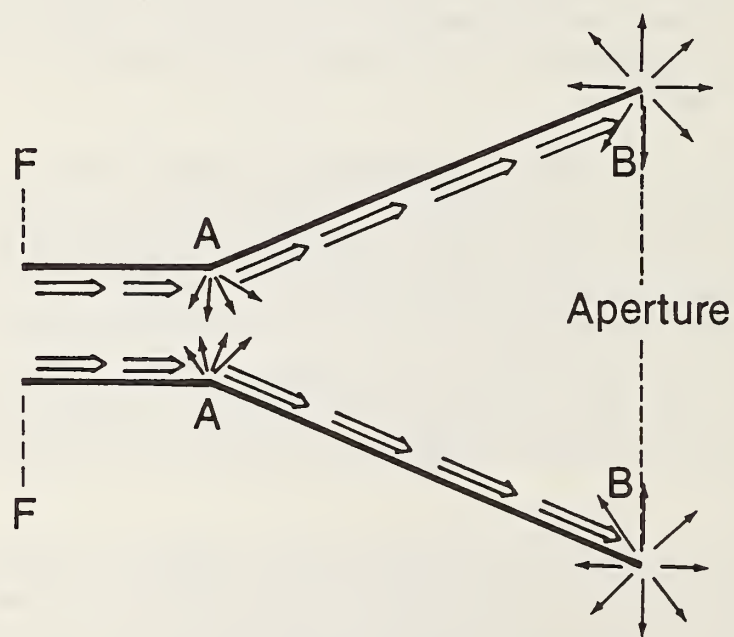


Figure 2. A schematic diagram of the interior horn surfaces indicating the surface currents and the diffraction points.

upper horn walls are drawn. The dashed lines show the butt geometry before the transitions are included. The narrow and wide dimensions of the wg are denoted by b_0 and a_0 respectively. The radius of the arc in the E-plane is r_e and in the H-plane it is r_h . The flare angles in these planes are ϕ_e and ϕ_h . Terzuoli & Peters [2] found that the reflection at the butt joint due to the diffraction is markedly reduced if the length of the arc $r_e\phi_e$ in the E-plane is 0.4λ or greater, where λ is the free space wavelength corresponding to the lowest frequency in the WR band, i.e. the *maximum* free space wavelength. To be safe the following relation is adhered to in the horn design (see figure 5 for z_0):

$$z_0 = 0.4\lambda. \quad (1.1)$$

This leads to

$$r = z_0 \sin\phi / (1 - \cos\phi) \quad (1.2)$$

or

$$r\phi \doteq 0.8\lambda \quad (1.3)$$

(twice the value suggested by Terzuoli & Peters) for both the E- and H-planes. Both r_e and r_h are determined from equation (1.2) by inserting ϕ_e and ϕ_h respectively. Up to this point only x_1 , z_0 , and the relation in equation (1.2) have been determined. The narrow aperture dimension b is found next.

Table 1. MINIMUM WG LENGTH x_1 FOR 0.1% OUTPUT ERROR

<i>WR</i>	<i>Freq Range(GHz)</i>	<i>x₁(cm)</i>
90	8.2—12.4	2.82
75	10—15	3.09
62	12.4—18	2.40
51	15—22	2.02
42	18—26.5	1.27
34	22—33	1.34
28	26.5—40	1.08
22	33—50	0.87
19	40—60	0.80
15	50—75	0.51
12	60—90	0.37
10	75—110	0.31

The reflection of the aperture as seen from the flare is a result of the edge diffraction at B in figure 2 and figure 4. The magnitude of the reflection is given by (see Appendix A)

$$\Gamma_{ap} = 0.0912/B^{1.22} \quad (1.4)$$

where

$$B \equiv b/\lambda \quad (1.5)$$

and b is the narrow (E-plane) dimension of the aperture. For the aperture reflection to be less than 0.01 equation (1.4) leads to the approximation

$$B = 6. \quad (1.6)$$

This equation and equation (1.5) determine the narrow aperture dimension in figure 4. To further reduce the aperture reflection quarter-round matching sections are attached to the H edges of the horn aperture perpendicular to the page at B in figure 4 (see figure 1 also). Analysis [3] indicates that if the radius of the quarter-rounds is 3λ (or greater) the edge diffraction is greatly reduced.

2. Braun Equations

Braun [4] specifies a set of relationships which, starting with a given gain, lead to an optimum horn design with approximately equal E- and H-plane beamwidths where the flare in both planes join the waveguide portion of the horn in a simple butt joint. The starting point for the noise standard horn design is equations (1.4) and (1.5), however, since an optimum horn gain is less important than obtaining a small internal aperture reflection. The Braun equations lead directly to

$$A = 468B/346 \quad (2.1)$$

and

$$l_e = 57600AB\lambda/(346 \times 468) \quad (2.2)$$

where A is the normalized (a/λ) broad dimension of the aperture, and l_e is the E-plane flare length in figure 4. The corresponding H-plane flare length is

$$l_h = l_e[(1 - b^2/4l_e^2)((1 - b_0/b)/(1 - a_0/a))^2 + a^2/4l_e^2]^{1/2}. \quad (2.3)$$

An approximate expression for the resulting gain g is

$$g = 10^6 AB/(346 \times 468). \quad (2.4)$$

It is clear from figure 4 and the equivalent figure for the H-plane that the flare angles are given by the equations

$$\phi_e = \sin^{-1}(b/2l_e) \quad (2.5)$$

and

$$\phi_h = \sin^{-1}(a/2l_h). \quad (2.6)$$

The corresponding r_e and r_h are then found from equation (1.2).

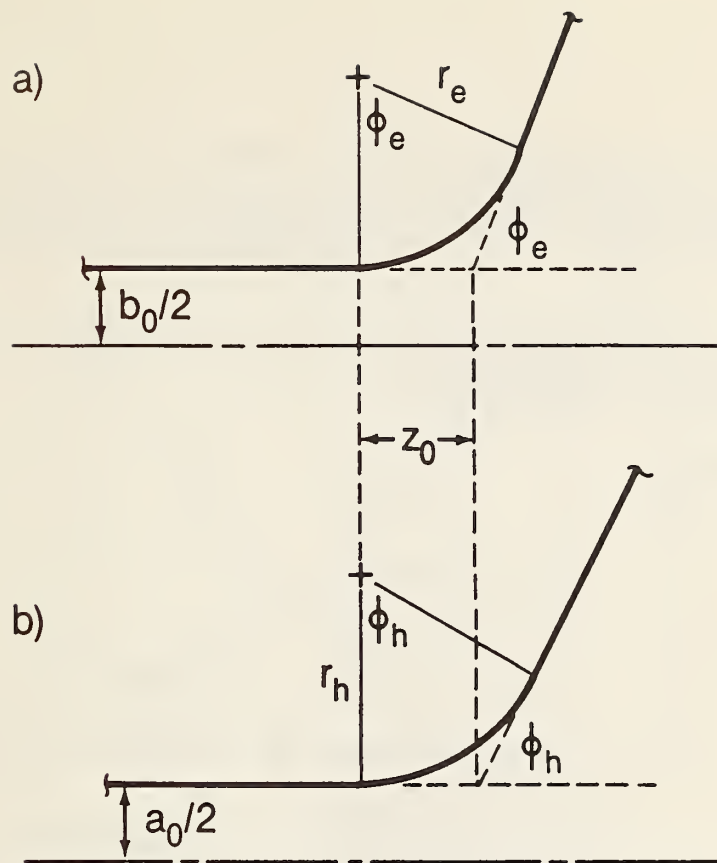


Figure 3. Cross sections of the upper halves of the E-plane (a) and H-plane (b) wg-flare transitions.

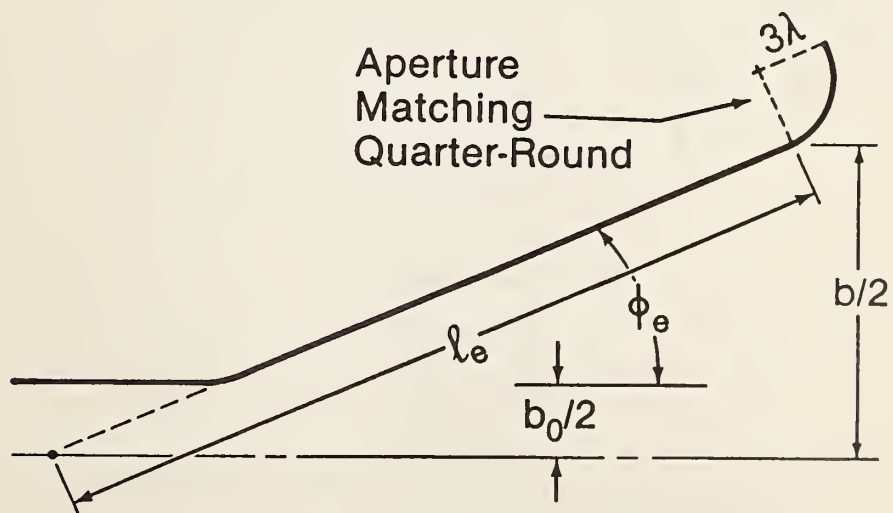


Figure 4. A cross section of the upper half of the E-plane interior surface.

3. Sundry Equations

The fundamental equations relating the electrical requirements of the horn to the internal horn dimensions have been presented in the previous two sections. Following are a number of derived equations that, although easily obtained, are included here for completeness and their usefulness in calculating machine drawing dimensions.

Figures 5 and 6 show cross sections of the E- and H-planes respectively in which the various dimension designations are self explanatory from previous discussions.

E-Plane Dimensions (figure 5)

$$\rho_e = b_0/2\sin\phi_e \quad (3.1)$$

$$x_2 = x_1 + z_0 \quad (3.2)$$

$$\Delta x_e = r_e \sin\phi_e - z_0 \quad (3.3)$$

$$\Delta y_e = r_e(1 - \cos\phi_e) \quad (3.4)$$

$$l_3 = (l_e - \rho_e)\cos\phi_e \quad (3.5)$$

$$x_5 = x_2 + \Delta x_e \quad (3.6)$$

$$x_6 = x_2 + l_3 \quad (3.7)$$

$$x_7 = x_6 - 3\lambda\sin\phi_e \quad (3.8)$$

$$y_7 = b/2 + 3\lambda\cos\phi_e \quad (3.9)$$

$$y_e = c_{1e} + c_{2e}(x - x_1) \quad (3.10)$$

H-Plane Dimensions (figure 6)

$$\rho_h = a_0/2\sin\phi_h \quad (3.11)$$

$$\Delta x_h = r_h \sin\phi_h - z_0 \quad (3.12)$$

$$\Delta y_h = r_h(1 - \cos\phi_h) \quad (3.13)$$

$$l_3 = (l_h - \rho_h)\cos\phi_h \quad (3.14)$$

$$x_4 = x_2 + \Delta x_h \quad (3.15)$$

$$y_h = c_{1h} + c_{2h}(x - x_1) \quad (3.16)$$

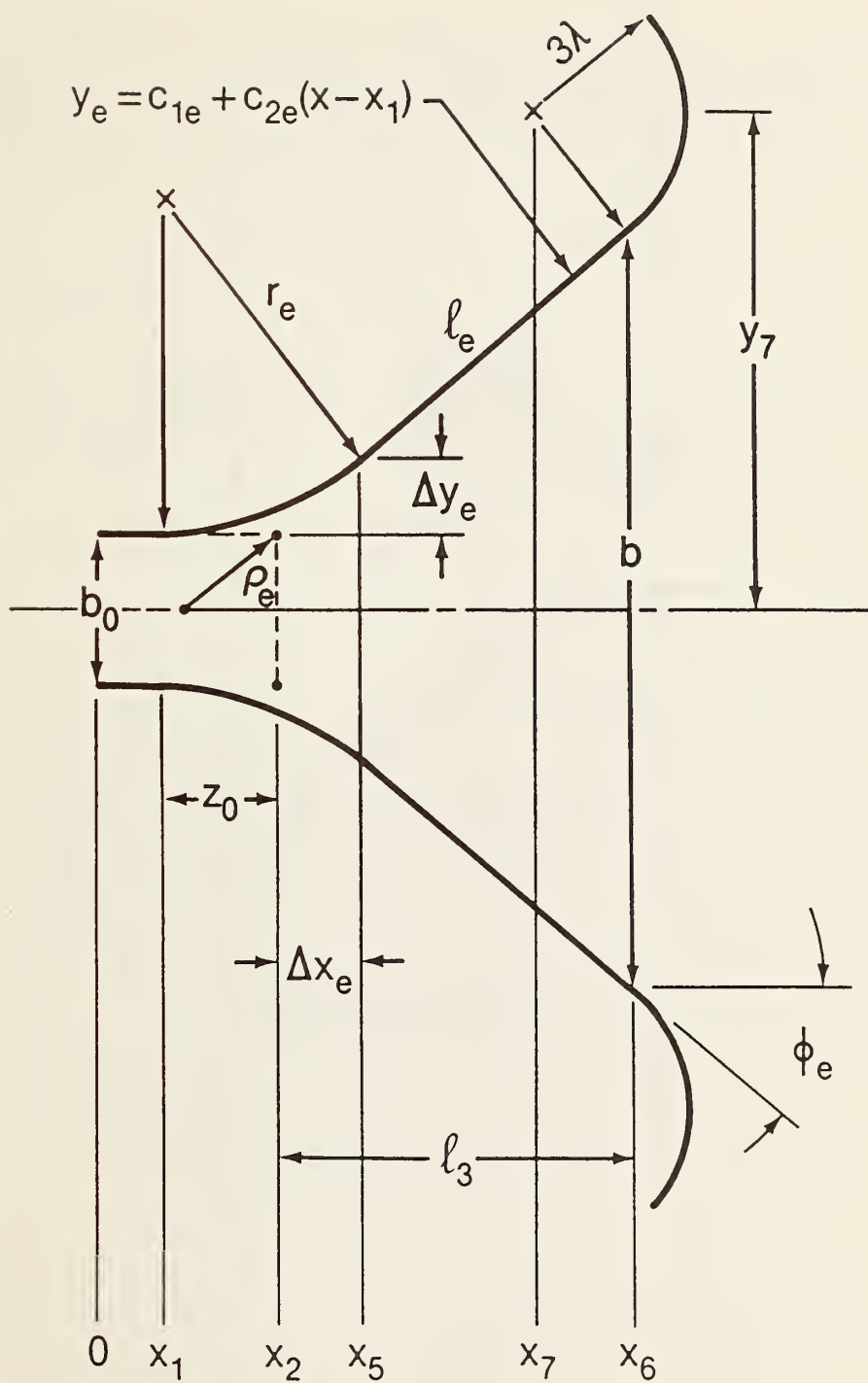


Figure 5. Cross section of the internal E-plane surface.

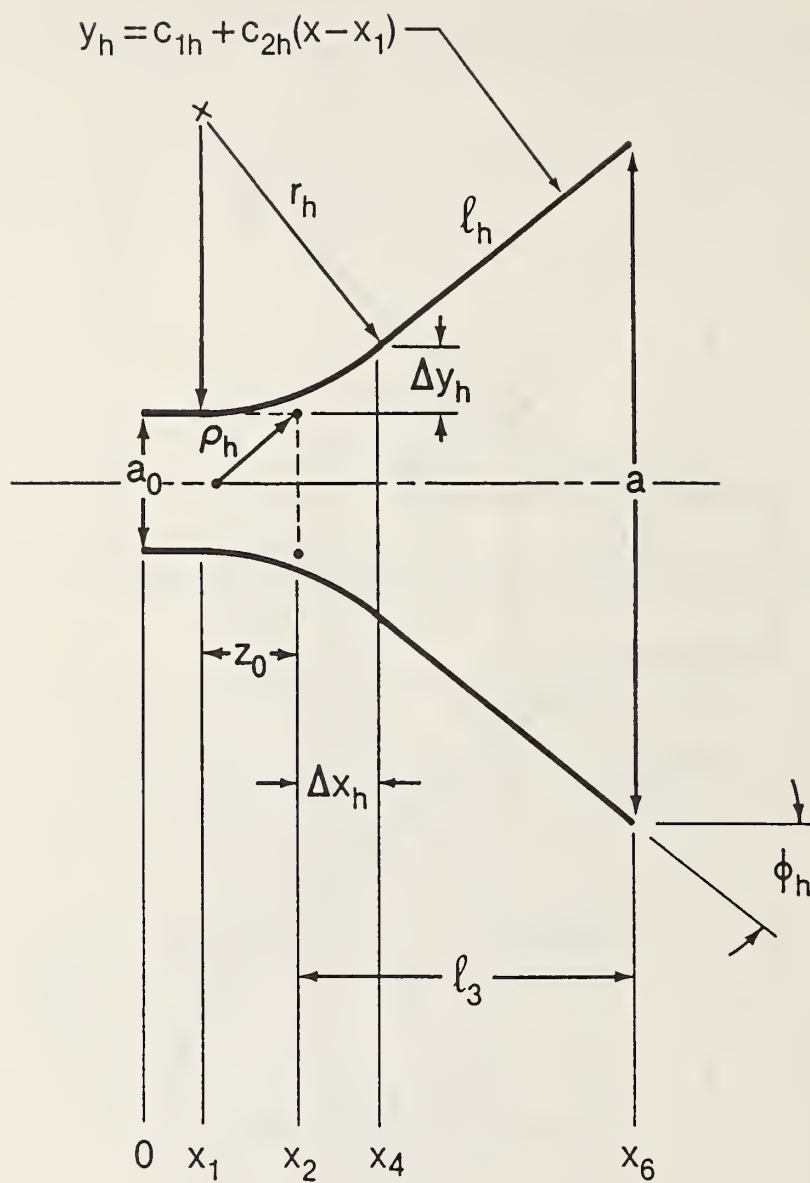


Figure 6. Cross section of the internal H-plane surface.

4. Results

Figure 7 is a photograph of the WR10 horn pickup that was designed and constructed according to the equations presented which ensure low internal reflections and an accurately calculable attenuation. Figure 8 is an isometric drawing of the same horn. The total internal reflection including the wg-flare transition and the aperture was measured to be less than 0.001. Analysis [1] shows the attenuation calculation to be accurate to $\pm 0.01\%$.

5. Acknowledgments

The Space Systems & Command, Control, & Communications, USAF, Washington, D.C.; and The Naval Ocean Systems Center (NOSC), San Diego, California funded much of the work leading to the millimeter wave horn pickup designs.



Figure 7. Photograph of the WR10 millimeter wave horn pickup.

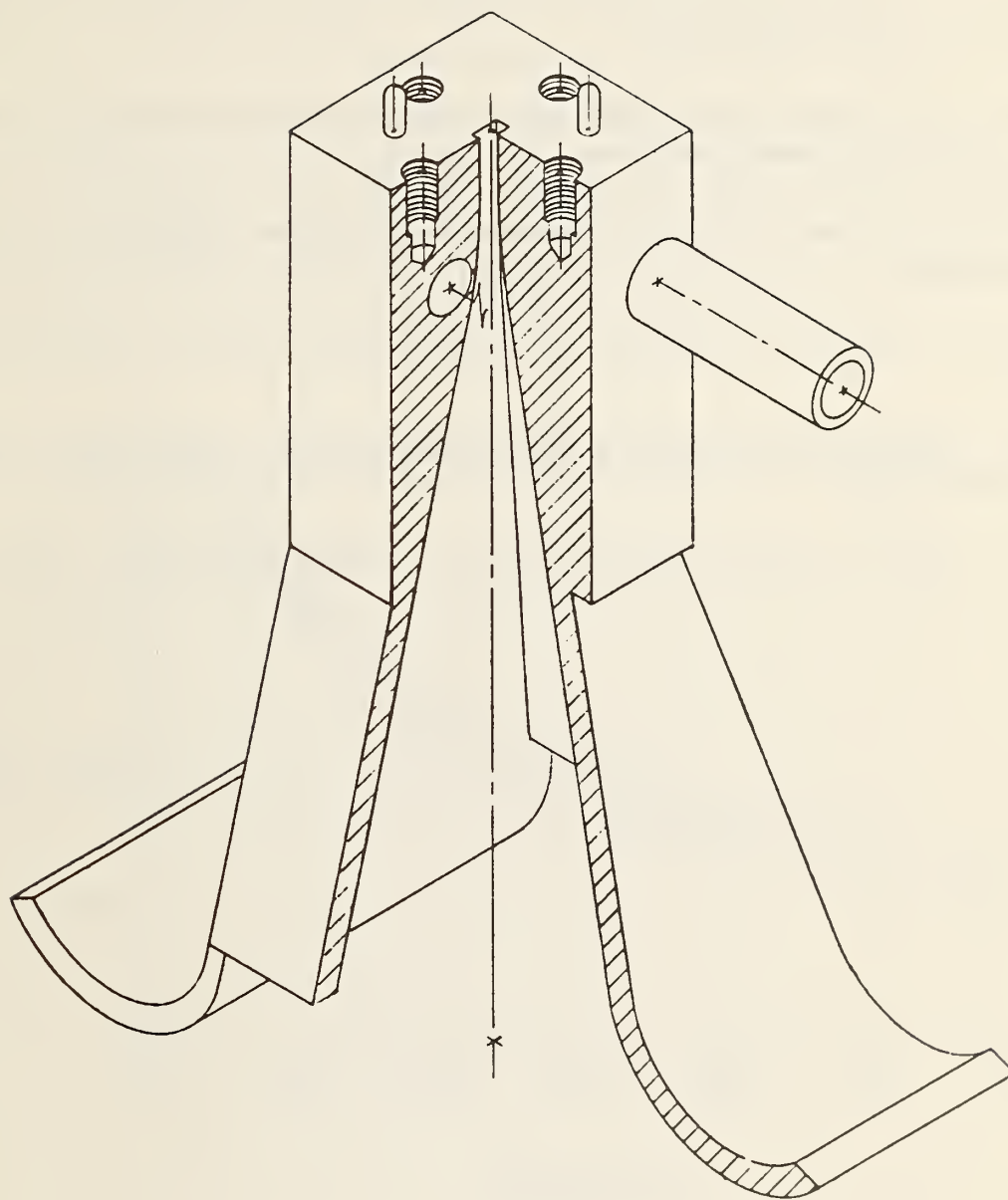


Figure 8. Isometric view of the WR10 millimeter wave horn pickup.

6. References

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- [5] Jull, E. V. Reflection from the aperture of a long E-plane sectoral horn. IEEE Trans., *AP-20*, No.1: 62-86; 1972 January.
- [6] Jull, E. V. Errors in the predicted gain of pyramidal horns. IEEE Trans., *AP-21*, 25-31; 1973 January.

Appendix A: Aperture Reflection

Jull [5] derives the following expression for the magnitude of the reflection seen from the flare portion of a sectoral horn:

$$\Gamma_{ap} = 1/4\phi_e k \ell_e \quad (A1)$$

where k is the free space wavenumber ($2\pi/\lambda$). Figure A1 shows a comparison of this formula with reflection data [6] from a pyramidal horn aperture as a function of $4\phi_e k \ell_e$, where the formula is plotted as the solid curve in the figure. The dashed curve is a least-squares fit through the data as a function of $(4\phi_e k \ell_e)^{-c}$, where the constant c was found to be 1.22 with a correlation coefficient of 0.98 for the fit. Recognizing that $2\phi_e \ell_e$ is the narrow aperture dimension b for small ϕ_e leads to equation (1.4), where B is the normalized aperture dimension.

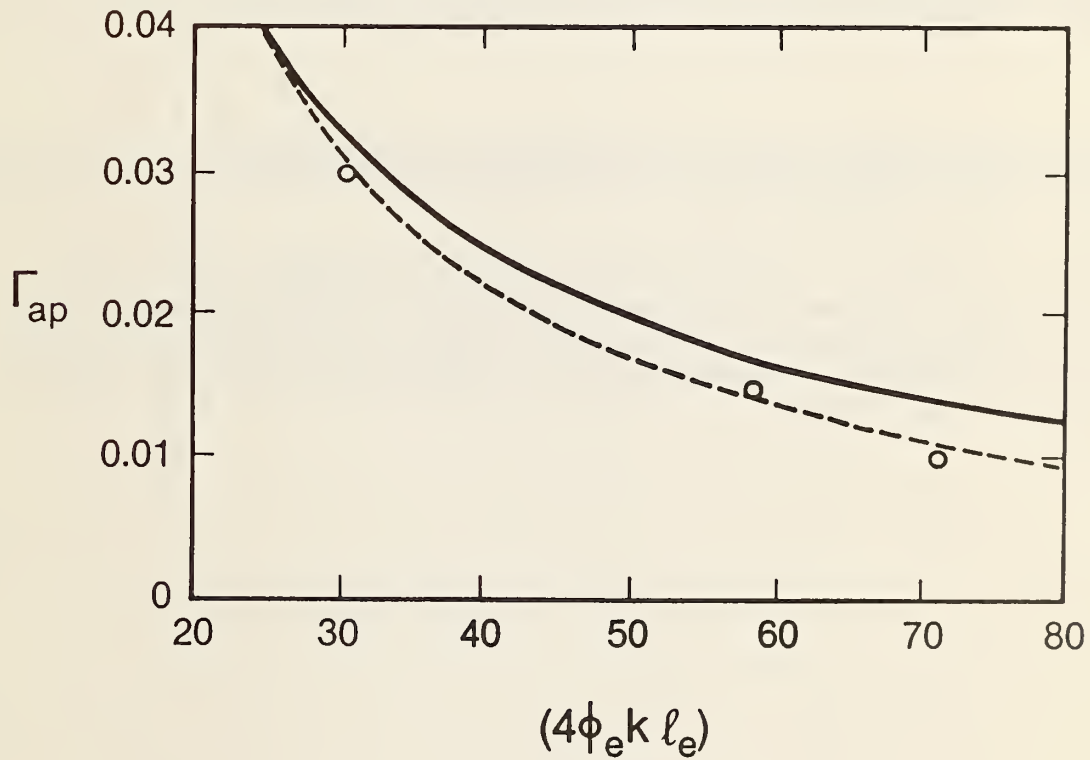


Figure A1. Internal aperture reflection for a pyramidal horn.

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